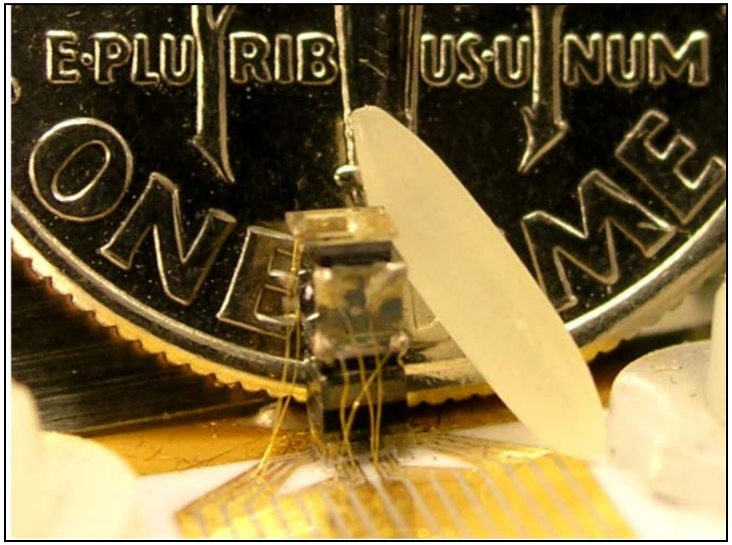
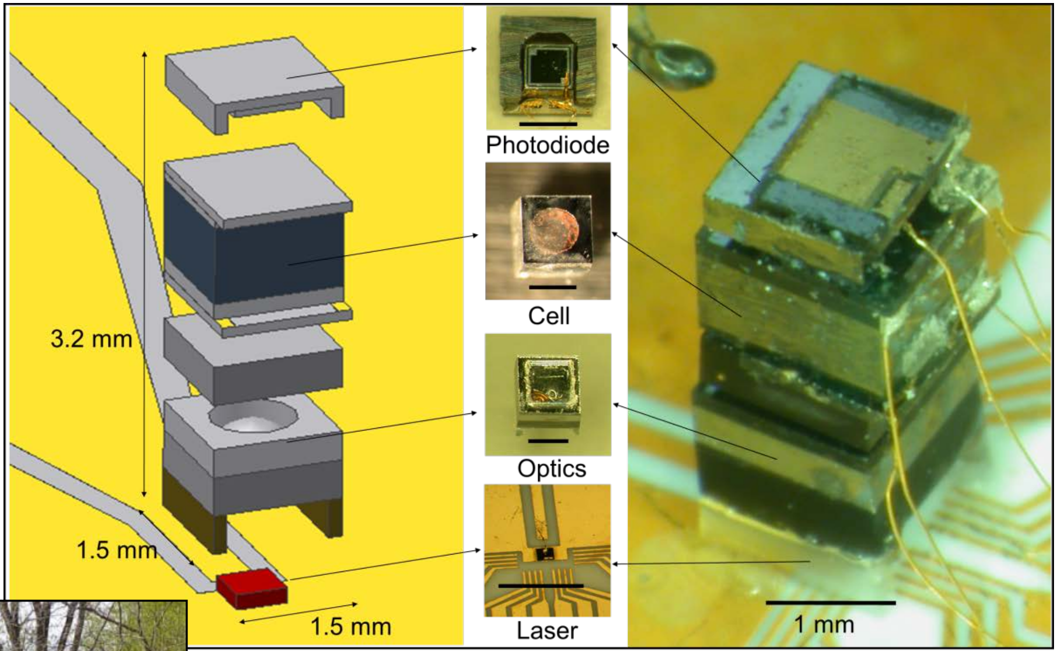
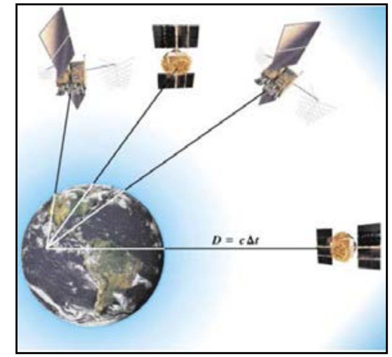
NIST Chip-Scale Atomic Device Program

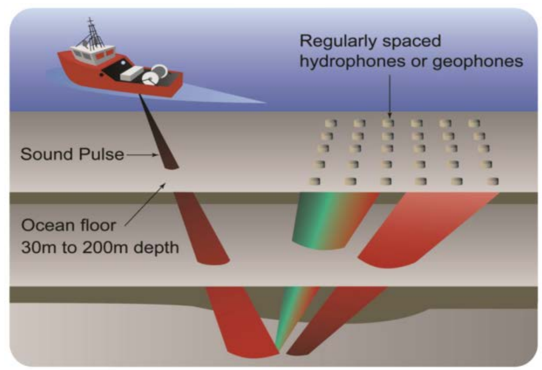


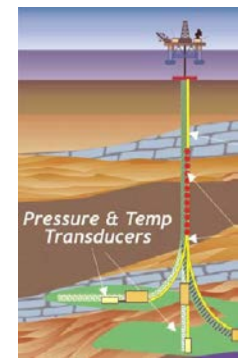


NIST Atomic Devices and Instrumentation Group led by John Kitching

Motivation







- Atomic-clock-quality timing and synchronization underpin a broad range of technologies and infrastructures.
- GPS, telecom, power distribution, surveillance, mineral exploration, space applications, etc. etc. 10^{-11} to 10^{-15} uncertainty.
- Many of these applications benefit from FIELDABLE atomic-clock-timing.

Motivation

- $1M.
- 10 m.
- 1,000 W.

10^{-15} clocks (0.1/month)

- Master clocks (long term synchronization)
- Secure communications
- Deep space navigation
- GPS Master clock (ground)

→

- $70k.
- 1 m.
- 50 W.

10^{-13} clocks (10/month)

- Large scale communications systems
- Power grids
- GPS Space Clocks
- Local synchronization

→

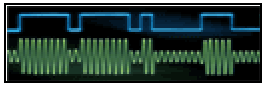
- $3k.
- 15 cm.
- 2 W.

10^{-11} clocks (1,000/month)

- Local communications hubs
- Instrumentation level flywheels

→

- $1k.
- 2 cm.
- 1 W.



10^{-9} clocks (100,000/month)

- Short haul navigation
- Local communications

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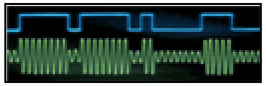

10^{-9} clocks (100,000/month)

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Opportunities for Improvement in fielded applications?
Size, weight, power, cost, performance, etc.

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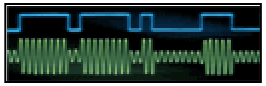


10^{-9} clocks (100,000/month)

- Short haul navigation
- Local communications

Ultraminiature clock?
10^{-11} and better.
$0.1k
0.1 cm
0.01 W

DARPA Chip-Scale Atomic Clock (CSAC) Program

- Stimulated by NIST pioneering demonstrations and follow-up workshops on ultraminiature atomic clocks ~1999.

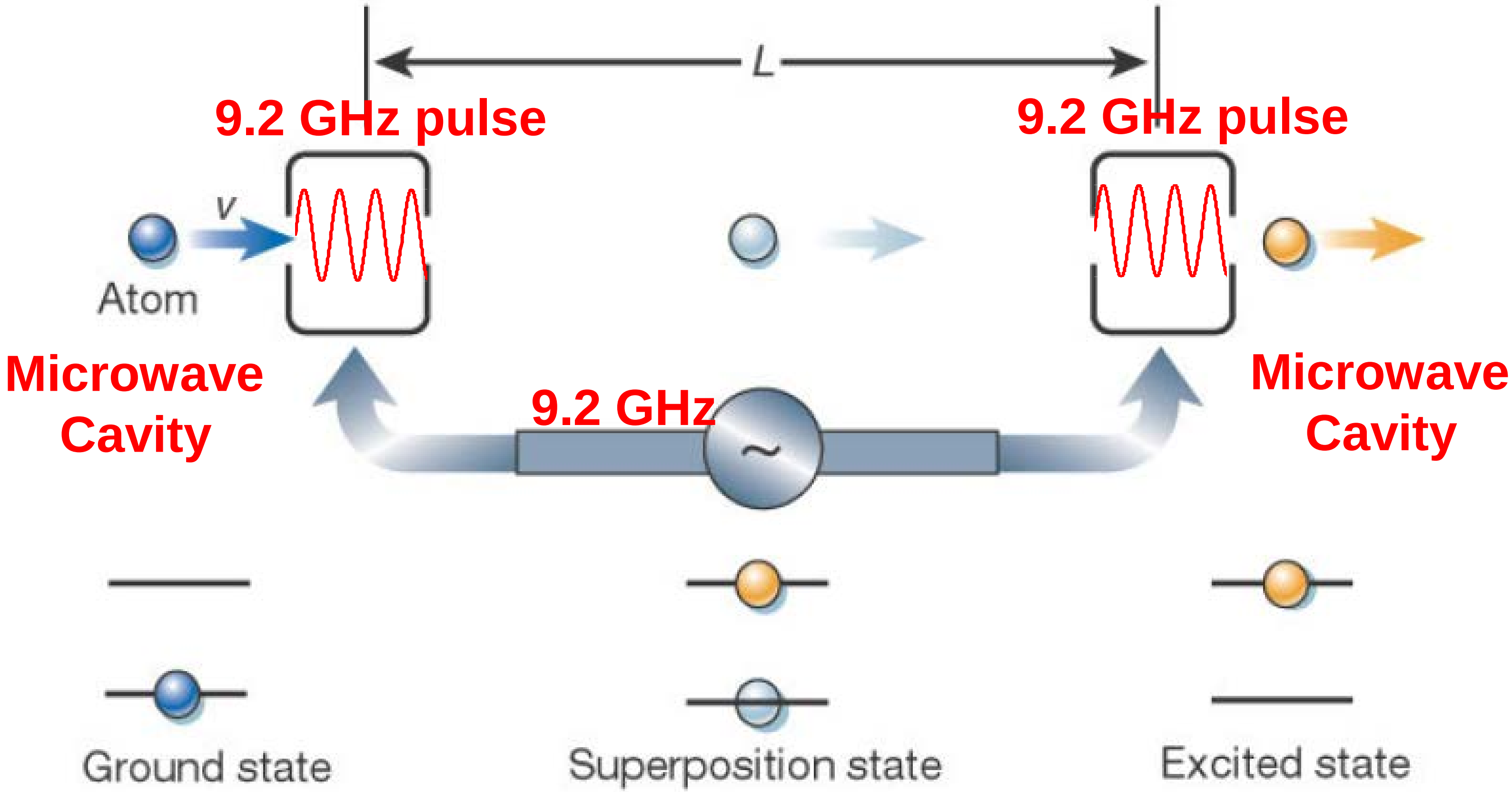
- Funded NIST to perform fundamental research and metrology.
- Funded companies to perform manufacturable demonstrations.
- Beginning 2002.

- NIST focus:
  - Coherent population trapping (CPT) as new approach eliminating need for large microwave cavity.
  - Use standard MEMS and microfabrication techniques to develop a device mass-manufacturable in principle.

- NIST outcomes;
  - World’s first chip-scale atomic clock 2004.
  - World’s first chip-scale atomic magnetometer 2005.
  - Follow-on program of broad range of chip-scale atomic sensors.
  - A feasibility demonstration of NIST on a Chip.

NIST Chip-Scale Atomic Clock (CSAC)

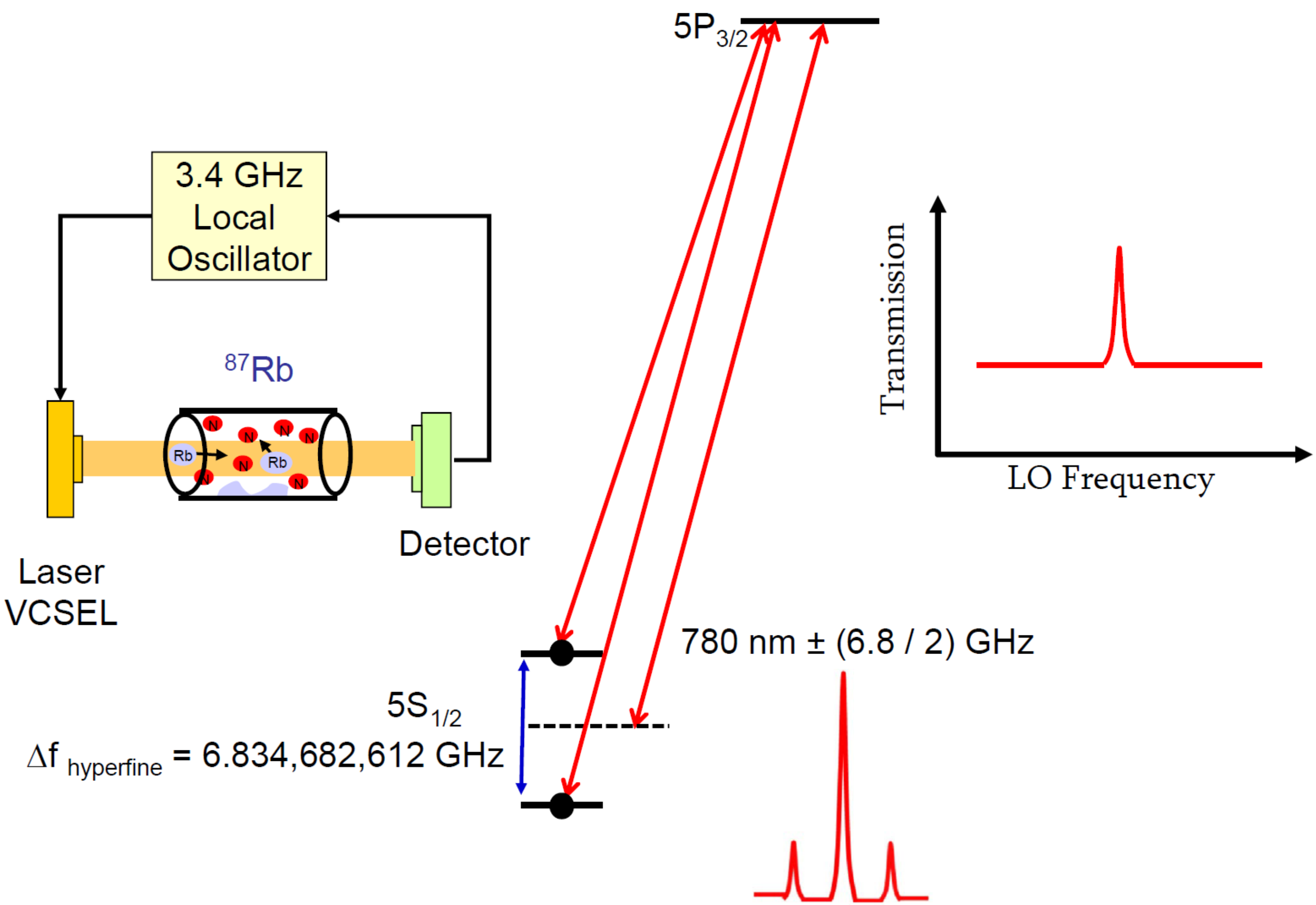
"Typical" high performance atomic clock



Requires microwave cavity on scale of several wavelengths (9.2 GHz ~ 3 cm).
Establishes fundamental minimum limit on size.

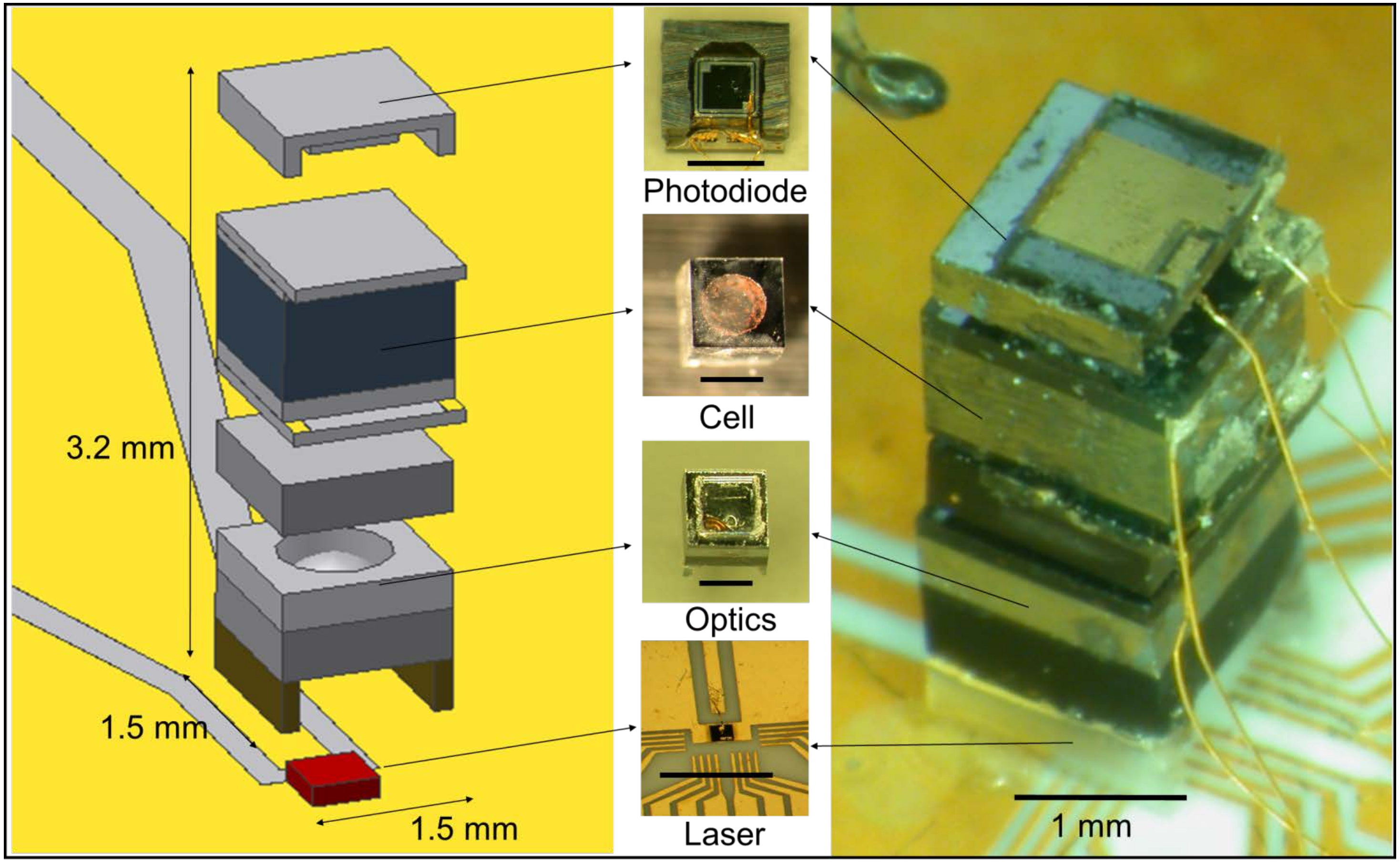
NIST Chip-Scale Atomic Clock (CSAC)

Coherent population trapping.
All optical approach. No microwave cavity needed.



NIST Chip-Scale Atomic Clock (CSAC)

Focus on manufacturability.
Use COTS where possible and standard MEMS fabrication.
Potential for wafer-level assembly.



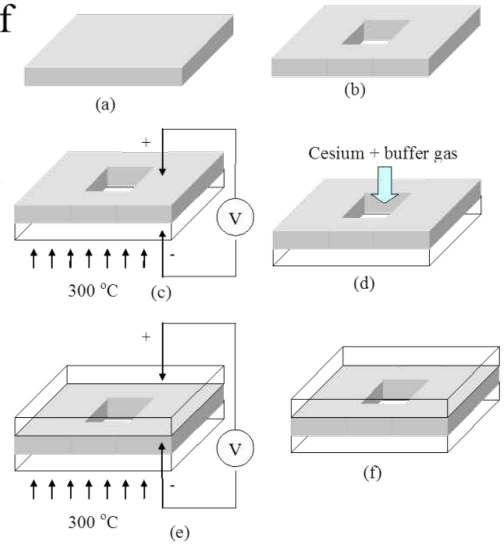
NIST Chip-Scale Atomic Clock (CSAC)

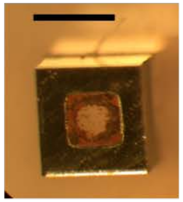
Atomic Vapor Cell a Challenge.

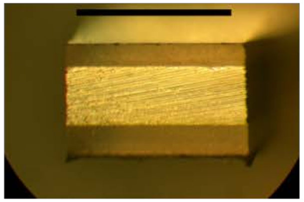
Cells Fabricated by Anodic Bonding

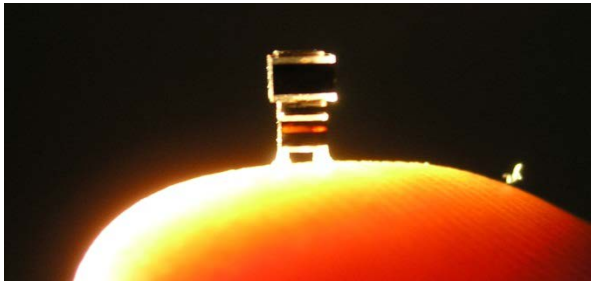
- Preform created by wet chemical etching or DRIE of Si wafers
  - Pyrex bonded on one side with anodic bonding
- Cell preform placed in anaerobic chamber for filling with Cs
  - Cs deposited using:

    $BaN_6 + CsCl \rightarrow BaCl + Cs + 3N_2$
  - Chamber back-filled with buffer gas and final bonding step carried out in chamber
- Diced cells made at NIST using the anodic bonding technique
  - Interior: 1 mm x ∅ 0.9 mm
  - Exterior: 1.33 mm x (1.45 mm)^2

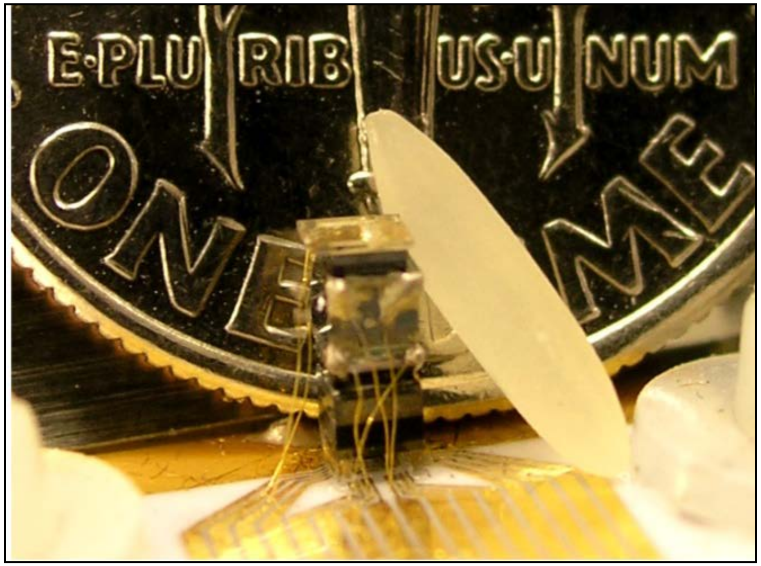








NIST Chip-Scale Atomic Clock (CSAC)



NIST world first CSAC demonstrated 2004.

10^{-11} uncertainty initially.
Stratum 1 telecom standard.

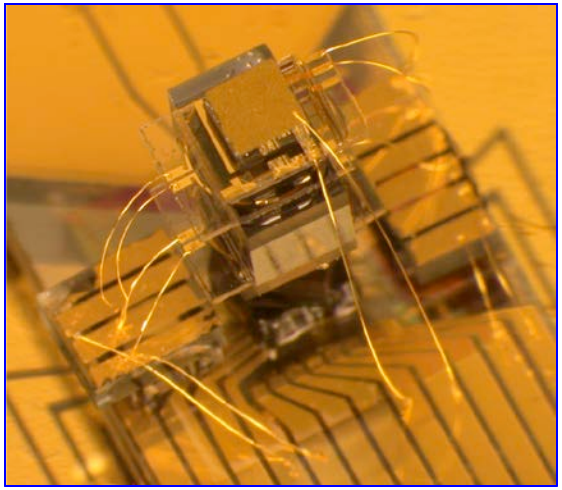
Improved to 10^{-12} uncertainty.

After demonstration, NIST transferred CSAC technology to manufacturers.

NIST focused on chip-scale atomic magnetometry.

Symmetricom: First commercial CSAC.
January 2011.
10^{-11} uncertainty.

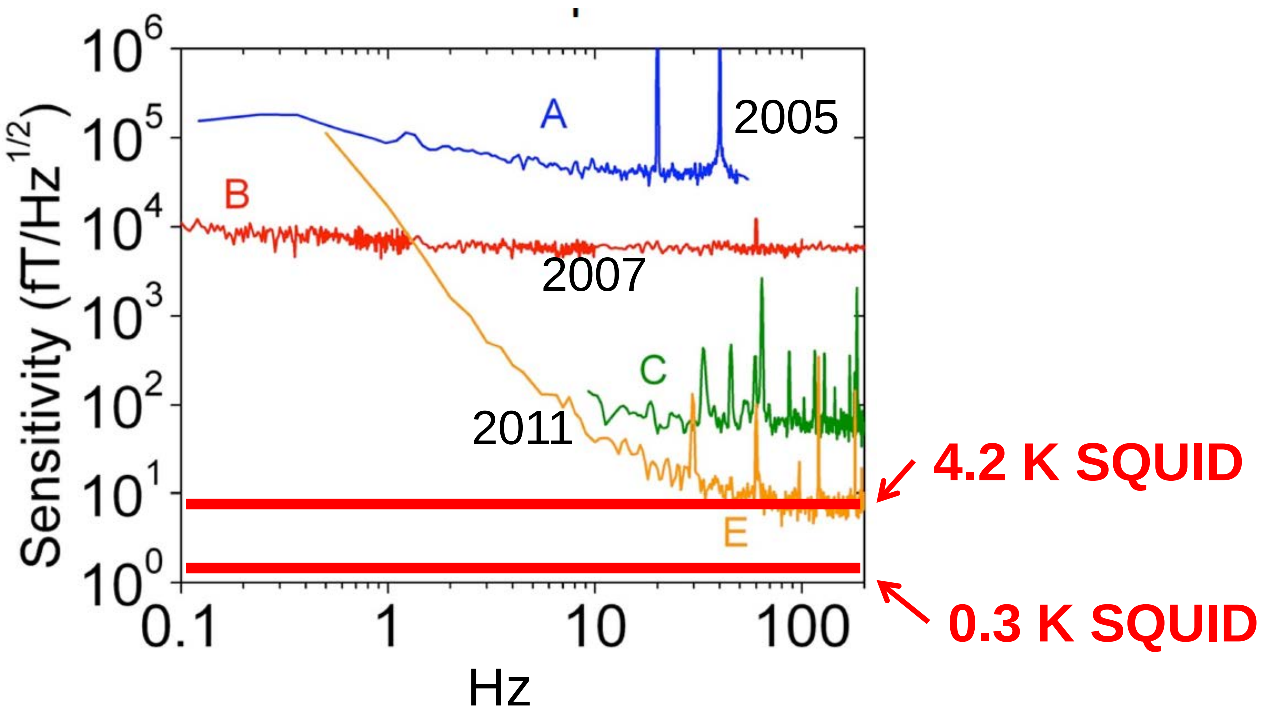
NIST Chip-Scale Atomic Magnetometer (CSAM)



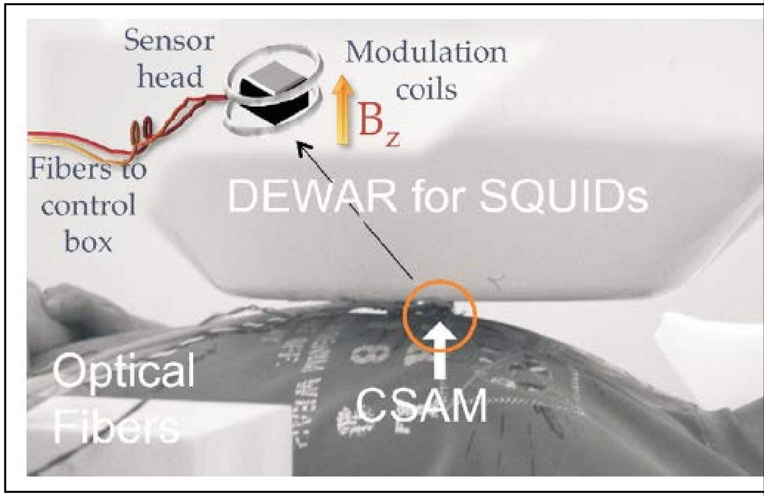
NIST world first CSAM demonstrated 2005.

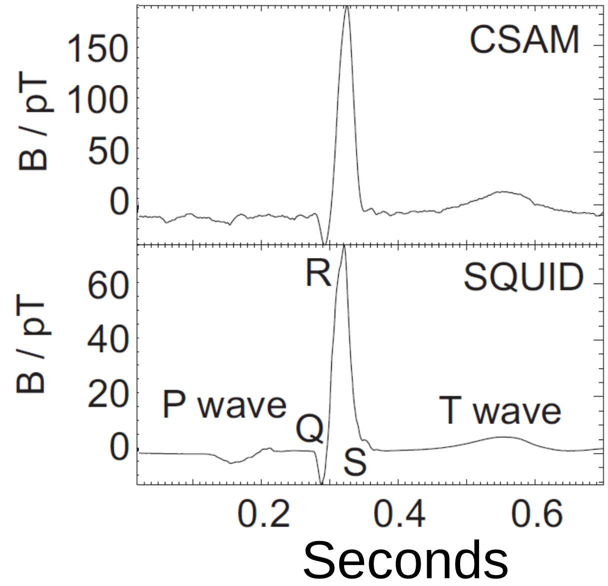
Modest performance initially.

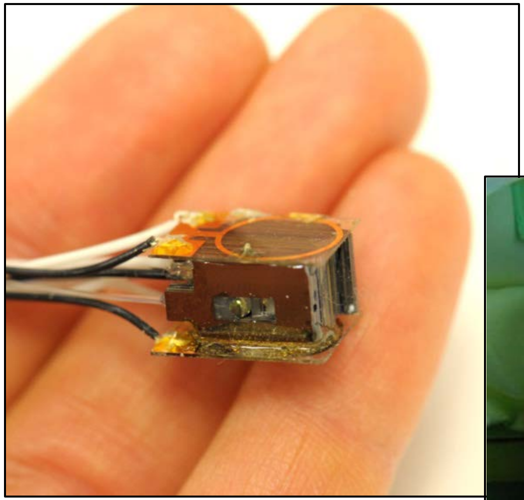
Performance rapidly improved to rival best in the world SQUID at 1,000,000 times smaller, 100 times less power, no cryogen needed, potential for low cost mass production.



NIST Chip-Scale Atomic Magnetometer (CSAM)





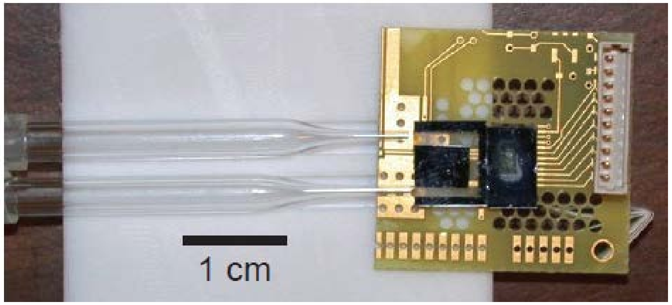


Biomagnetic fields.

Heart, brain, muscles.

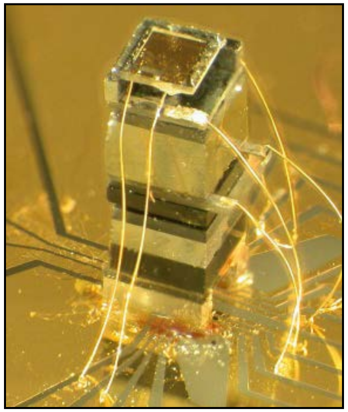
NIST Chip-Scale Atomic Device Program

Some current research directions.



Zero-field NMR for “remote” chemical analysis and zero-field MRI.

Biomagnetic field measurement arrays for diagnostics/imaging on heart, brain, muscles. Brain/machine interface.



NMR gyroscopes/accelerometers.

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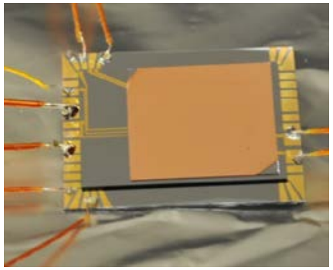
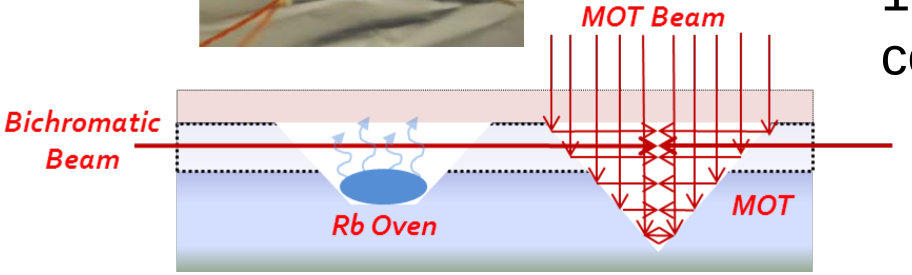
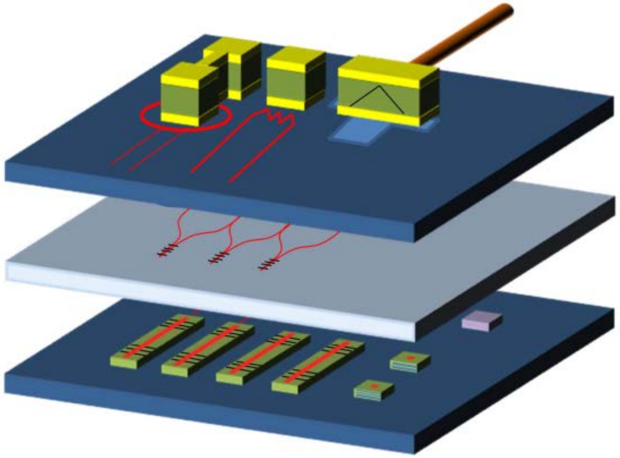




Cold-atom chip-scale atomic devices.
Clocks, magnetometers, gyros, etc.
1,000x performance improvement compared to standard CSAD.

Time, Electrical, Magnetic, Force, Temperature, Length, etc.



NIST on a Chip.

NIST Chip-Scale Atomic Device Program

- More than 130 scientific publications.
- 8 patents (most include external partners).
- Dozens of conferences and workshops.
- Dozens of postdocs and grad students trained, many going to industry jobs related to atomic sensors.
- Multiple national and international scientific awards.
- NIST/DoC awards.
- Broad recognition in technical and public press.
- On-going intense interest and funding from other Federal agencies.